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Spatial assessment of the bioenergy potential of forest residues in the western province of Spain, Caceres

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ABSTRACT

The present work is mainly devoted to provide a rigorous analysis on the quantification, the mapping and the management of the bioenergy potential of forest residues from the most representative forestry species of the west-central region of Spain (Cáceres).

An appropriate methodological approach for the estimate of potential biomass and potential bioenergy as well as the use of GIS for data process are both crucial for the design of thermal plants and for the accurate estimate of biomass collection and transportation costs, according to the scale economy of the plant.

The total forest residues in the province of Cáceres are estimated as 463 000 t y^{-1}. The availability of such major biomass potential for energy production is strongly conditioned to the inherent difficulties during the extraction process. This way, an energy potential of 139 000 toe y^{-1} would be achieved if the above-mentioned biomass collection rate is assumed.

The method to optimise the search for suitable locations for thermal plants as well as for biomass extraction/collection areas, based on the combined use of GIS and spatial analysis techniques, is also described.

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1. Introduction

Biomass is the furthest developed of renewable energy sources. It provides 35% and 3% of the primary energy needs of developing and industrial countries, respectively [1]. There is hence a clear need for deeper inquiry into the techniques currently available for its efficient management. Unlike the case of fossil fuels, the net rate of carbon dioxide emission during biomass combustion is the same as that of carbon dioxide absorbed during growth of the equivalent forest mass. This way, biomass contribution to the greenhouse effect might be regarded as negligible, thus enforcing the above-mentioned need for further research on such energy source [1].

One of the main hindrances to biomass energy management is the difficulty of ensuring a steady supply for heat or electricity generating plants. Therefore, the viability of any project involving biomass as energy source will largely depend on both the availability of the resource and its management. Nonetheless, identifying and assessing the potential of different forest species for energy purposes is a priority task that is being undertaken in most of developed regions worldwide in order to replace fossil fuels and hence contribute to biosphere sustainability.

The forested area of the central regions of Spain approaches 50% of their total. Forestry activities generate significant quantities of wastes and by-products that are suitable for diverse energy purposes. The estimate of energy

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Nomenclature

A_n	area occupied by tile *n* (ha)
ABI	annual biomass increment (kg dry mass)
ADI_n	annual diameter increment (cm y^{-1})
D	diameter
D_n	normal diameter (cm)
LHV	lower heating value (toe t^{-1})
P_{av}	available energy potential (toe)
Q_{av}	annual mass of available dry biomass (t)
R	radius (cm)
toe	tons of oil equivalent
Y_n	annual residue parameter (expressed in t ha^{-1}), i.e. available residual biomass suitable for power production according to the predominant species in tile *n*.

production from such biomass source – i.e. the energy potential – thus becomes a matter of interest in those regions.

Integrating this biomass into a particular business activity (like those related to electricity generation, solid or liquid fuels, composting, etc.) would favour collection, although biomass supply usually involves high associated costs.

The dominant area (50%) in the regions referred to in the present work is typically covered by *dehesa* woodland, characterised by an averaged 39% wooded density and a secondary vegetation cover mainly represented by diverse pasture species [2,3]. The remaining area (11%) corresponds to various shrub species and – primarily – *Pinus pinaster* woods [3]. Current regulations specifically forbid industrial exploitation of such areas for timber industry. This way, only wastes from sylviculture/arboriculture activities and other residues are available as biomass supply.

Nevertheless, the use of such residual biomass has become crucial for several reasons. Firstly, its removal is the most effective way to prevent forest fires which wreak such havoc on local economies of affected areas. Secondly, it favours employment and profitability of forestry activities, and finally – but not least – it might contribute to the development of bioenergy crops, which again would lead to employment enforcement in rural areas provided that the farming output would have a guaranteed market.

Forest fires, construction of dams, alternate management of forestry installations, etc. lead to continuous variation of woodland features, which makes the estimate of available biomass for a hypothetical power plant quite a difficult task. As a consequence, GIS tools based on regularly updated maps and satellite imaging are regarded as a being particularly useful, provided that they allow a straightforward and accurate quantification of available resources in a concrete target area.

The application of GIS-based techniques to the estimate of biomass potential is relatively recent. The first available reference, which features the spatial distribution of woodland in Tennessee (USA) through GIS multilayer analysis in order to provide suitable locations for the installation of thermal plants [4], dates back only to 1996. After this introduction of GIS into the field of biomass management, there followed various studies aimed at mapping the potential for power production from agro-forestry residues in different areas and regions, both in and outside our country. One of the primary uses of these mapping analyses was the definition of regional strategies concerning the use of biomass [5–7]. Some other works in the scientific literature are devoted to the description of GIS-based methods to determine the spatial distribution of different crops and forestry species through the definition of specific residue parameters for each of them, in order to quantify the estimated biomass availability. This allows the association of the potential energy obtained for each of the crops or forestry species to the municipal or county codes of the corresponding boundary map. The sum of the energy values for each crop yields a single value that defines the potential energy from biomass for a given municipality or county [8–11].

One of the major problems of biomass management is the cost associated to collection and transport activities. As will be noted below, GIS-based techniques are of particular utility in assessing the costs of biomass supply at a regional level, and hence as a notable support for decision making relating this particular issue [12,13]. An evaluation of the biomass energy potential of the main forest residues in the province of Cáceres, located in west-central Spain, is carried out in the present work. For that purpose, a GIS was used both for the geographical representation of the biomass resource and as an inestimable tool for operation and management activities.

Four stages were developed for the estimate of the biomass potential. (i) Determination of the theoretic biomass potential in terms of the previous location and estimate of the annual quantities of biomass generated by the most representative forestry species in the area under study. (ii) Available biomass potential obtained via the selection of the main forestry species in the region on the basis of the two following aspects: extension of their regional distribution and difficulties in the collection process due to steep terrain or some other drawbacks. (iii) Energetic characterisation of biomass and determination of technical feasibility for power production. (iv) Consideration of the fact that operations are based on the environmental potential, since the biomass derives from conventional forestry activities and from clearing of underbrush in access tracks for fire prevention.

The energy production potential of forest residues considered in each of these stages was mapped and managed using the broad range of possibilities offered by GIS.

Cáceres, located in west-central Spain (Fig. 1), is one of the nation's 50 provinces. Its area covers 19 868 km^2, thus being Spain's second largest province after Badajoz, which together constitute the Autonomous Region of Extremadura. The province of Cáceres is divided into 10 subregions (roughly the equivalent to *county* in the Spanish territorial division), as shown in Fig. 1.

Specific data and some other relevant information processed in this study was mainly obtained from

- the agrarian subregion boundaries of the province of Cáceres,
- the digital version of the Third National Forest Inventory for the province of Cáceres (IFN3) [14],

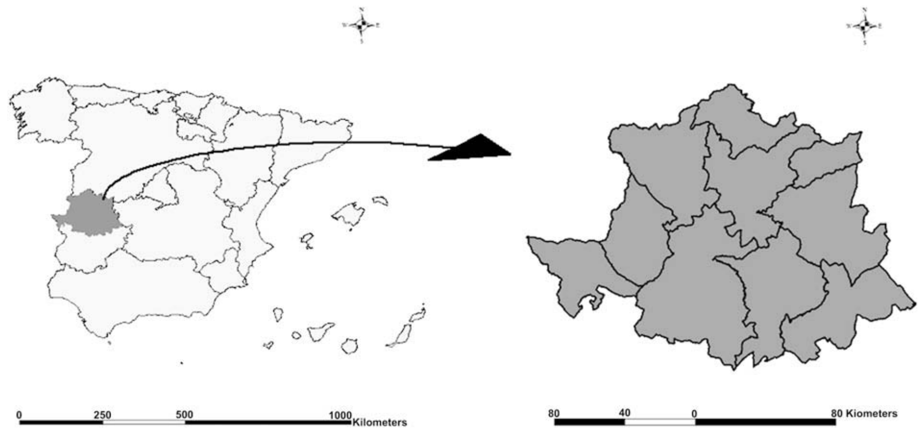


Fig. 1 – The target study area: province of Cáceres. Subdivision lines define 10 subregions.

- the *MAPA* slope map, which had to be previously digitised for its use by GIS [15], and
- the road map of the province of Cáceres.

As described in next section, the forestry species and groups of species of IFN3 for the Province of Cáceres were considered, i.e. *P. pinaster*, *Pinus pinea*, *Quercus ilex*, *Quercus suber*, *Quercus pyrenaica*, *Castanea sativa*, *Eucalyptus camaldulensis*, as well as some other hardwood and riparian tree species. The spatial distribution of such main forestry species can be seen in Fig. 2, according to the IFN3.

2. Methods

2.1. Estimate of production of forest residues

A good approach to estimating the stock of biomass and its annual usable production is to use the concept of stratum, as

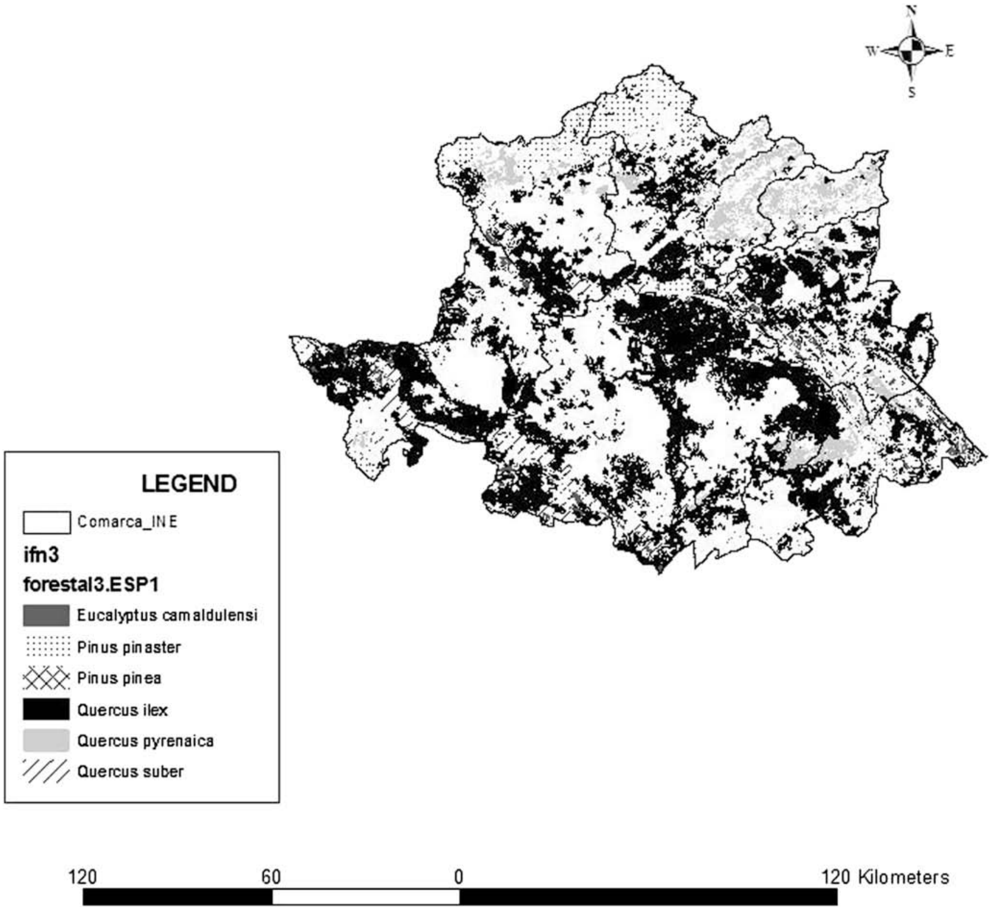


Fig. 2 – Spatial distribution of forest species according to IFN3.

defined in the Third National Forestry Inventory, IFN3 [14]. A stratum characterises the type of arboreal vegetation according to the species present in a particular zone, their states in terms of mass and the fraction of tree cover per area. It might therefore be regarded as a homogeneous concept in terms of statistical description, provided that the target variable to be estimated in the present work is the annual biomass production. Specific information concerning such strata is available at the Spanish Forest Map (MFE 50.000) [16], and most notable features for the particular case of the province of Cáceres are listed in Table 1.

The methodology followed is based on the biomass fractions introduced by Montero et al. [17], but only for tree branches less than 7 cm in diameter from pruning and from natural branch fall (except in the case of eucalyptus, for which all fractions were quantified provided that current legislation allows felling activities). Such a method develops a logarithmic model which relates the normal diameter of the tree to the net dry biomass and has the following analytical form:

$$\ln Y = a + b \ln(D_n) \quad (1)$$

where Y represents the biomass for each fraction (expressed in kg dry mass), D_n the normal diameter in cm and a and b are the two specific regression parameters.

This model allows straightforward calculations and improves – in general terms – the goodness of the statistical analysis. However, the final result should be multiplied by a correction factor – obtained from the standard deviation of the estimate – in order to eliminate the bias introduced by logarithmic transformation. The parameters a and b as well as the bias correction factor take different values depending on the species under consideration.

Expression (2) yields the annual biomass increment (ABI), D_n being the normal diameter in cm and ADI_n the annual increment in diameter (also expressed in cm y^{-1}). The dry biomass difference between two consecutive years defines the annual biomass increment for given biomass fraction, species and diametric class [17]. Calculations of such increments for the particular case of *P. pinaster* were performed as described, using an Excel spreadsheet program. Results are listed in Table 2.

$$\mathrm{ABI} = f(D_n + \mathrm{ADI}_n) - f(D_n) \quad (2)$$

The normal diameter for each species and stratum was then calculated using data available at Table 301 of IFN3, and was found to be 19.55 cm for *P. pinaster*. An extrapolation was performed from data of Table 2 to estimate the annual biomass increment (in kg tree^{-1}) for each particular species and stratum.

Finally, the combination of those annual biomass increments with the forestry density values (in trees ha^{-1}) available at the document IFN3 of the province of Cáceres yielded the biomass estimates for each stratum listed in Table 3, expressed in t ha^{-1}.

Table 1 – Basic features of the strata from IFN3 of Cáceres.

Stratum	Predominant forest species	Occupation (%)	Mass stage	Covered fraction (%)
01	*Pinus pinaster*	≥70; 30 < Esp. < 70	Sawtimber, poles	70–100
02	*P. pinaster*	≥70; 30 < Esp. < 70	Sawtimber, poles	40–69
03	*P. pinaster*	≥70; 30 < Esp. < 70	Sawtimber, poles	20–39
04	*P. pinaster* with *Quercus ilex*, *Quercus suber* or *Quercus pyrenaica*	30 < Esp. < 70	All	20–100
05	*P. pinaster*	≥70	Saplings. Seedlings	5–100
06	*Q. pyrenaica*	≥70	All	70–100
07	*Q. pyrenaica*	≥70	All	40–69
08	*Q. pyrenaica*	≥70	All	20–39
09	*Q. ilex*	≥70	All	70–100
10	*Q. ilex*	≥70	All	40–69
11	*Q. ilex*	≥70	All	20–39
12	*Q. suber*	≥70	All	40–100
13	*Q. suber*	≥70	All	20–39
14	Low-forested *Q. ilex*	≥70	All	40–100
15	Low-forested *Q. ilex*	≥70	All	20–39
16	Low-forested *Q. ilex* and *Q. suber*	30 < Esp. < 70	All	20–70
17	Low-forested *Q. suber*	≥70	All	20–100
18	Low-forested *Q. pyrenaica* and other species	30 < Esp. < 70	All	20–100
19	Low-forested *Q. ilex* with understocked forest and dispersed	≥70; 30 < Esp. < 70	All	5–19
20	*Castanea sativa*	≥70	All	20–100
21	*Arbutus unedo* with other species	≥70; 30 < Esp. < 70	All	20–100
22	*Eucalyptus camaldulensis*	≥70	All	70–100
23	*E. camaldulensis*	≥70	All	20–69
24	Brushwood with understocked forest and dispersed	≥70; 30 < Esp. < 70	All	5–19
25	River trees	≥70; 30 < Esp. < 70	All	5–100

“Occupation (%)” represents the percentage occupation of the predominant forest species, “Mass stage” represents the stage in the development of the referred species, and “Covered fraction (%)” represents the percentage of land covered by the horizontal projection of vegetation.

Table 2 – Annual increments of biomass for each species and diametric class (DC), expressed in kg tree^{-1}, for *Pinus pinaster*.

DC (cm)	Increments in biomass fractions (kg tree^{-1})	
	Branches 2–7 cm	Branches < 2 cm
5	0.00	0.07
10	0.44	0.25
15	0.47	0.54
20	0.31	0.82
25	0.43	1.08
30	0.58	1.39
35	0.71	1.63
40	0.92	2.03
45	1.08	0.60
50	1.28	2.67

Table 3 – Annual residue estimators (t ha^{-1}), according to the stratum and to the predominant species.

Stratum	Predominant stands	Estimador de incremento anual de biomasa (Y) (t ha^{-1})
01	*Pinus pinaster*	1.069
02	*P. pinaster*	0.499
03	*P. pinaster*	0.172
04	*P. pinaster* with *Quercus* (*ilex*, *suber*, or *pyrenaica*)	0.443
05	*P. pinaster*	0.179
06	*Q. pyrenaica*	0.833
07	*Q. pyrenaica*	0.374
08	*Q. pyrenaica*	0.167
09	*Q. ilex*	0.517
10	*Q. ilex*	0.258
11	*Q. ilex*	0.197
12	*Q. suber*	0.302
13	*Q. suber*	0.115
14	*Q. ilex*	0.202
15	Dehesa woodland of *Q. ilex*	0.139
16	Dehesa woodland of *Q. ilex* or *Q. suber*	0.146
17	Dehesa woodland of *Q. suber*	0.091
18	Dehesa woodland of *Q. pyrenaica* or other species	0.201
19	Sparsely wooded *Q. ilex* dehesa	0.091
20	*Castanea sativa*	1.582
21	*Arbutus unedo* with other species	0.244
22	*Eucalyptus camaldulensis*	7.477
23	*E. camaldulensis*	4.946
24	Scrub with scattered trees	0.070
25	Riparian forest	6.956

2.2. *Available quantities*

For both technical and economical reasons, the collection of residual biomass should not be carried out in areas of steep slopes (areas with slope steeper than 20% will therefore be excluded), nor in those located further than 3 km from roads or passable tracks. This way, areas with slope below 20% located less than 3 km from a road or a passable track are regarded as optimum for residual biomass collection.

The annual available quantities of dry biomass (expressed in t) will be obtained as:

$$Q_{av} = \sum_n A_n Y_n \qquad (3)$$

where A_n represents the suitable area for collection in tile n (ha) and Y_n the annual residue estimator, which indicates the available annual residual biomass for energy production expressed in t ha^{-1} (including tree branches 2–7 cm in diameter and twigs less than 2 cm), depending on the predominant species of tile n (see Table 3).

2.3. *Available energy potential*

The energy potential can be defined as the expected energy production from the residual biomass obtained as described in the previous section. It represents the total amount of forest residues from the selected species in a region that is available for energy production purposes, and may be regarded as the upper limit for the value of energy that can be obtained from such kind of wastes. The analytical expression used for the estimation of the residual biomass is the following:

$$P_{av} = Q_{av} \times \text{LHV} \qquad (4)$$

where LHV represents the lower heating value (toe t^{-1}) and P_{av} the available energy potential (toe). Results for the latter variable corresponding to the strata considered in the present work are listed in Table 4.

2.4. *Implementation of the method in a geographic information system*

The program package ArcInfo v.8.3 was used in the present study. The tools of ArcInfo are structured as three applications whose combined use allows access to all of the package's functionality: ArcMap, ArcCatalog and ArcToolbox. This enabled the combined use of the different data sources needed to quantify the biomass and its potential in the target area in a reliable and easy-to-update form. The estimators used to quantify the biomass residues were obtained following the procedure described below.

As was seen above, the following factors need to be determined in order to estimate the annual biomass from forest residues produced by forestry activities (and therefore the potential amount of fuel available for energy generation):

- The area (ha) occupied by the stratum that will generate that residue.
- The area that is actually usable in terms of technical constraints.

The information contained in IFN3 corresponding to the province of Cáceres was used to determine these two factors with the support of the GIS. The methodological approach followed for such purpose is summarised in Fig. 3, and the usable area is shown in Table 4.

The area occupied by each subregion and stratum was obtained from IFN3 and the corresponding subregion map. Provided this inventory includes the pertinent areas and strata,

Table 4 – Annual biomass usable for energy production (t), and theoretical and actual available energy potential in the province of Cáceres (toe y^{-1}).

Stratum	Usable area (ha)	Available energy biomass (t)	Available potential (toe)
01	21977.87	23 490.7	10 427.8
02	15921.35	7941.8	3525.7
03	5648.61	969.9	430.7
04	16000.38	7088.1	3147.1
05	16211.20	2907.2	1290.7
06	8050.57	6705.5	2657.2
07	18497.37	6922.5	2743.2
08	8427.52	1405.3	557.0
09	20060.84	10 395.8	4353.4
10	72699.23	18 756.9	7870.8
11	46165.01	9072.4	3807.2
12	31836.86	9603.4	3874.7
13	22016.86	2521.8	1017.6
14	140525.15	28 436.7	12 068.1
15	238522.64	33 196.0	13 934.1
16	29095.87	4246.9	1782.6
17	26838.02	2433.9	982.2
18	17566.30	3565.8	1401.9
19	62437.57	5699.2	2258.5
20	8887.11	14 058.0	–
21	16625.87	4083.2	–
22	8945.93	66 890.1	25 550.9
23	19148.71	94 710.7	36 135.4
24	56783.45	3957.2	
25	6271.14	43 622.2	
All	935161.43	413 557.2	

the area by stratum belonging to the pre-defined region was simply selected within ArcMap application. This led to the straightforward classification of these areas according to stratum and region, eliminating Stratum-0 which corresponded to non-forested areas (rivers, towns, roads, etc.).

As was noted above, the study was designed to account for environmental and economic restraints on the use of biomass deriving from forest residue. One of such restraints lies in the fact that biomass residues should not be extracted from areas of steep slopes, nor from those with difficult access or too far from roads or passable tracks.

Fig. 3 is a schematic representation of the procedure used to determine the forested area that could be used for energy production. The extraction of biomass was considered only for slopes less than 20% since, in addition to not being economically viable, steeper terrain might involve erosion and soil loss problems. The area of the province with slopes less than 20% was determined according to the following procedure: (i) the zone was reclassified starting from its slope layer in the GIS, assigning the value "1" to the areas involving slopes below 20%, and "0" to those with steeper slopes; (ii) layers of slopes below 20%, which were obtained with the GIS from the basic topographical data, were merged; (iii) using the identifier fields that would appear in the final layer, the polygons that met all the established criteria were selected to generate a new layer with all the zone's usable areas.

In a further step, an *availability layer* was defined in order to determine accurately the residual biomass that could be collected from areas close to roads or passable tracks. Such new layer was obtained as described next: (i) using a specific software application of ArcMap, and taking the road map of the province of Cáceres as reference, the distance to the closest road was estimated for each of the points of the map. (ii) Starting from the previous distance mapping process, the value "0" was assigned to distances higher than 3 km, whereas the closest to a road was labelled as "100". The final result was therefore an *availability layer* or *availability map* according to a proximity-to-road criterion.

The layer of the entire forested area capable of producing forestry biomass, i.e. that created from IFN3, was then "trimmed" by forming an intersect overlay with the layer of

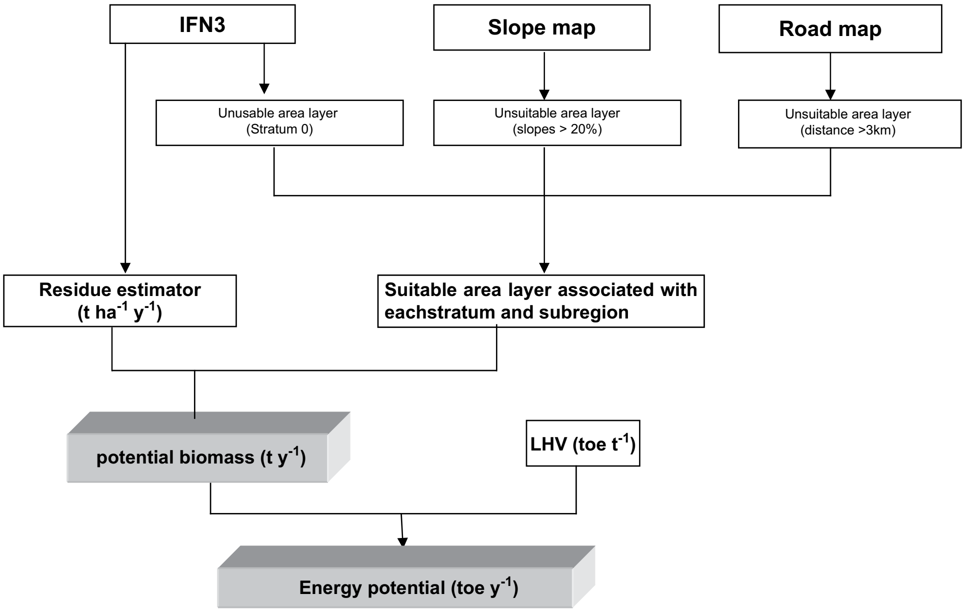
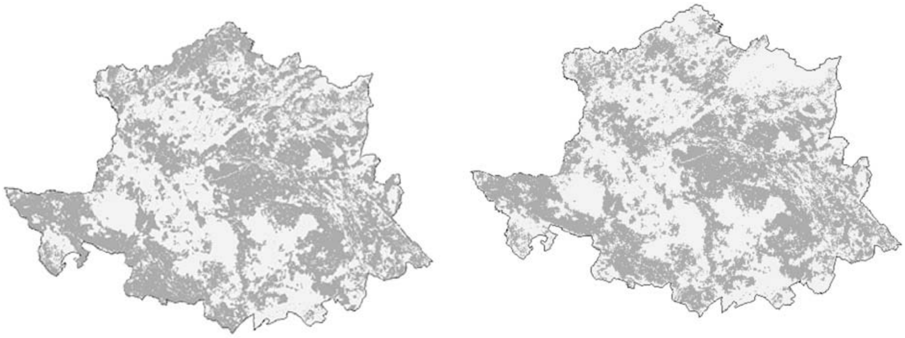

IFN3
Slope map
Road map
Unusable area layer (Stratum 0)
Unsuitable area layer (slopes > 20%)
Unsuitable area layer (distance >3km)
Residue estimator (t ha^{-1} y^{-1})
Suitable area layer associated with eachstratum and subregion
potential biomass (t y^{-1})
LHV (toe t^{-1})
Energy potential (toe y^{-1})

Fig. 3 – Schematic diagram of the method followed to determine the biomass energy potential of the target area.



i) Areas capable of producing forestry biomass.

ii) Areas suitable for forestry residue biomass.

Fig. 4 – Map of Cáceres: (i) area capable of producing forest biomass (dark shaded) and (ii) effective area for forest biomass exploitation (slopes below 20%).

the zone's usable areas (slopes below 20%). The effects of this process are shown in Fig. 4. The final estimation of available biomass was carried following these three steps: (i) importing the IFN3 data into a table that contains the information of the estimators and heating values for each species; (ii) calculation of the quantities; and (iii) graphical representation of data.

With these estimates of available biomass, the energy potential was determined as the product of the table containing the annual quantities and that containing the LHV by stratum and predominant species, according to Eq. (4). The result was a new field containing the values of available energy potential for each element of the table, expressed in toe y^{-1}. The available potential is defined as the energy contained in the biomass which can be technically and economically used for energy production purposes.

3. Results

Table 3 lists the residue estimators for each stratum and species usable for energy production.

According to San Miguel [2], biomass production in *dehesa* woodland reaches 900–1100 kg ha^{-1} y^{-1}, or 300–1540 kg ha^{-1} y^{-1} (wet mass) and 210–1080 kg ha^{-1} y^{-1} (dry mass) as referenced by Montoya [3]. This same author gives an estimate of 1000–2500 kg ha^{-1} y^{-1} (wet mass, which corresponds to 700–1750 kg ha^{-1} y^{-1} dry mass) for biomass production if holm oak mount is considered instead of dehesa.

In the case reported here the available biomass from dehesa ranged from 352 to 1251 kg ha^{-1} y^{-1}, depending on the stratum and on the dominant forest formation (dehesa,

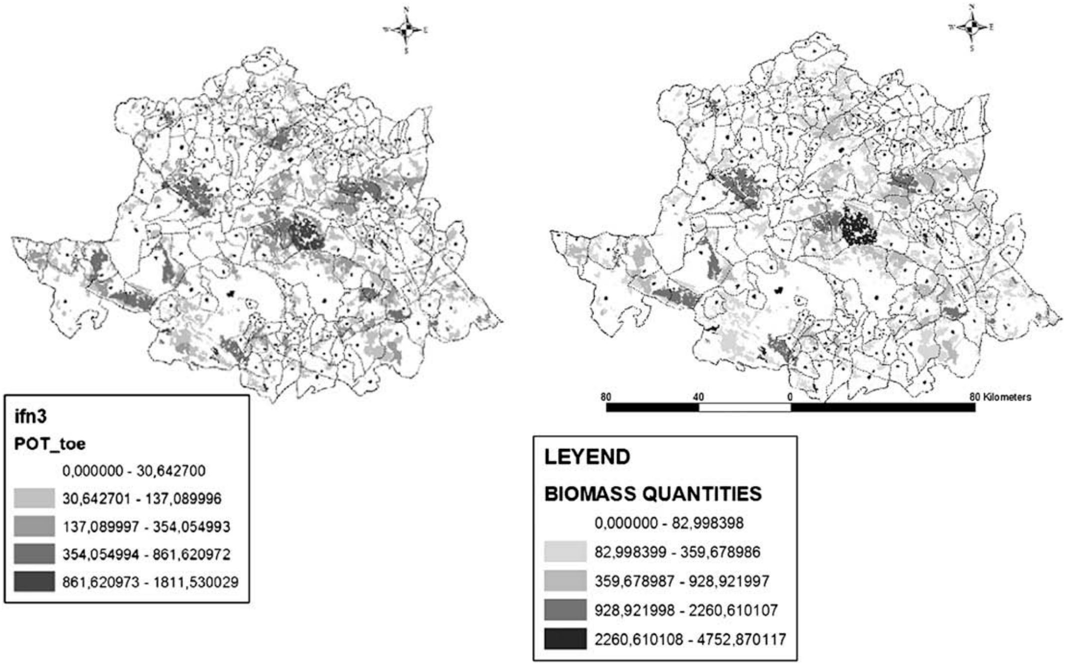


Fig. 5 – Final maps of: (i) energy potential (toe) and (ii) annual quantities of forest biomass (t).

Table 5 – Heating values (MJ kg^{-1}) of the types of residue under study.

Biomass residues	LHV wb MJ kg^{-1}	LHV db MJ kg^{-1}
Eucalyptus residue	14.96	15.97
Pine residue	9.09	18.6
Cork oak slash	13.6	16.9
Holm oak slash	14.33	17.58
Pyrenean oak slash	13.1	16.6

low-forested holm oak areas, etc.). Such values approximately meet those mentioned in the preceding paragraph. It must be noted that only the fraction of biomass suitable for energy production (thin branches with diameter ranging between 2 and 7 cm) was taken into account in the calculation of the energy potential. This is the reason why values between 91 and 517 kg ha^{-1} y^{-1} were achieved for the corresponding estimators.

Estimators for *P. pinaster* forest ranged from 171 to 498 kg ha^{-1} y^{-1}, which approximately meet those obtained by Perez Ortiz and Esteban Pascual [9] (150–510 kg ha^{-1} y^{-1}) in a research work performed in Soria, a central province of Spain. Also, values between 166 and 832 kg ha^{-1} y^{-1} were achieved in the present work for *Q. pyrenaica*, while values 200–450 kg ha^{-1} y^{-1} were obtained by the above-mentioned authors in the province of Soria.

The fact that the estimates for the annual biomass production presented here approach those obtained by other authors in earlier studies should be regarded as a validity test for the method described in the previous section.

Table 4 lists the annual quantities of forestry biomass and their uses for the province of Cáceres. The north of Cáceres possesses a major biomass potential, with 463 000 t y^{-1} estimated forestry residue rate. Table 4 also presents the availability of the biomass exploitable for energy purposes under the constraints of the difficulties in the extraction/collection activities. Assuming that all of this could be collected, an energy potential of 139 000 toe y^{-1} would be achieved (Fig. 5).

In order to calculate the energy potential, the forestry species that would be suitable for exploitation were selected on the basis of two aspects: the quantities of usable residue for energy production and the technological feasibility of such use. With these premises, the selected species were: *P. pinaster*, *P. pinea*, *Q. ilex*, *Q. suber*, *Q. pyrenaica* and *E. camaldulensis*. Table 5 presents the heating values used to determine the energy potential of the various types of biomass under study [18]. These heating values were used to calculate the values of both the theoretical and available energy potentials. The results are listed in Table 4. As can be deduced from them, there is no appreciable difference between the theoretical potential and the potential available after ruling out areas with slopes greater than 20%. However, the reason for this lies in the fact that only 4 out of the 10 subregions in the province of Cáceres are affected by slopes exceeding 20%. Indeed, the same comparison for these subregions alone gives a difference in percentage between the theoretical and the available potentials approaching 50%. Therefore, an appropriate quantification of the biomass should account for this factor.

The specific features of the economy of scale restrict the design of energy plants to those with a minimum production capacity of at least 5 t h^{-1}. This corresponds to a need for 51 200 t y^{-1} of raw material, which would generate 41 000 t y^{-1} biomass rate after torrefaction. Also, for transport cost reasons, the areas of supply of biomass must lie within a radius of 30 km from the plant, as indicated in Ref. [9].

Taking into account the above-mentioned premises, the GIS was used to search for the most suitable locations for energy plants. A detailed analysis of such possible locations (considering factors like low energy potential, inadequate sloped terrain, access from road or passable tracks, existence of river beds, etc.) allowed the final suggestion of an optimum one. Fig. 6 shows the spatial location of these plants, as well as the theoretical radius of their raw material supply.

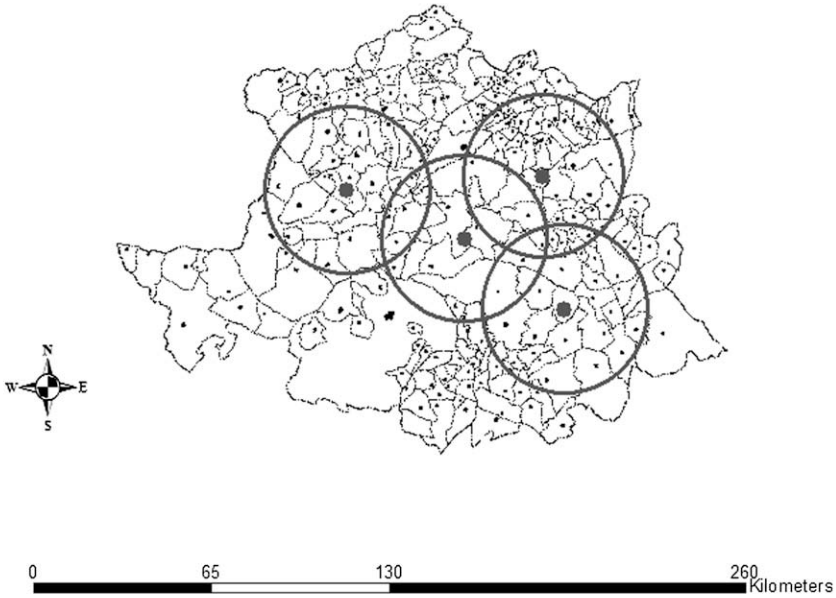


Fig. 6 – Suggestion for optimal location of energy plants from biomass supply.

4. Conclusions

Finally, from the display of results shown in Fig. 6, the following assertions can be made:

- The Spanish province of Cáceres possesses a vast biomass potential. In particular, 463 000 t y^{-1} forest residues are estimated, which yields an equivalent energy potential of 139 000 toe y^{-1}.
- Steep slopes play a drastic role in the biomass extraction/collection activities, reducing the effective area down to almost one half in certain zones of the north of Cáceres (involving slopes exceeding 20%). Such factor should be rigorously taken into account when performing any estimation relating biomass quantification.
- Proximity of collecting areas to roads or passable tracks should also be accounted for, provided that the feasibility of the energy plant is to a greater of lesser degree influenced by transport costs.
- It must be note that figures represent potential quantities. Actually, one might strongly depend on the frequency of performing the forestry activities that generate the residue biomass.
- It should also be borne in mind that Regional and National Government Authorities must contribute to the conservation and maintenance of the *dehesa* woodland (extensive areas of parkland grazing-forestry systems based on Q. *ilex* and Q. *suber*), which will promote the creation of new enterprises to carry out the forestry tasks involved.
- Finally, it should be mentioned that, as the techniques of exploiting forestry resources improve – and the continual supply of quality product is guaranteed – the forest residues considered in the present study could come to replace, at least in part, the fuels that are currently being used.

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